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USE OF GPS (GLOBAL POSITIONING SYSTEM) FOR DYNAMIC  
POSITIONING OF HYDROGRAPHIC SURVEY PLATFORMS(U) DEFENSE  
MAPPING AGENCY WASHINGTON DC P J FELL ET AL 01 DEC 06

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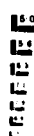
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Use of GPS for Dynamic Positioning of  
Hydrographic Survey Platforms

by

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ABSTRACT

The Navstar Global Positioning System of navigation satellites may be exploited in several ways to support dynamic positioning of hydrographic survey platforms. Range observations from four satellites provide direct positioning in the World Geodetic System 1984 (WGS 84) terrestrial coordinate frame with an accuracy from 16 meters for the Precise Positioning Service (dual-frequency ranging) to 76 meters for the Standard Positioning Service (single-frequency ranging), spherical error probable. Higher precision is obtainable, especially for near-shore survey applications, using simultaneously measured phase observations acquired at sea and at land-based control points. With this method of positioning, the dynamic path of the survey vessel may be obtained with accuracies better than 1 meter. In addition to these applications, GPS may be utilized to determine survey vessel attitude and to establish undersea acoustic transponder control. This paper presents a synopsis of actual and anticipated results for each of these hydrographic survey applications.

1.0 INTRODUCTION

The Navstar Global Positioning System (GPS) is a satellite-based radio navigation system designed to provide continuous all-weather navigation to appropriately equipped users on a worldwide basis. (Payne, 1982). The operational system, will consist of 18 satellites in circular orbits having 55-degree inclinations and orbit periods of about 12 hours. This geometry provides global visibility of four to seven satellites. Each satellite carries an atomic clock providing long-term stability. Navigation signals consisting of spread spectrum, pseudorandom noise (PRN) signals on two coherent L-band frequencies are transmitted continuously. The GPS code receivers decode the PRN signals to obtain orbital elements, time calibration data, and measurement data.

Although the navigation services provided by GPS will satisfy many requirements for marine navigation, greater positional accuracy may be required to support specialized survey operations. This paper will explore the potential for alternative applications of GPS to hydrographic survey operations.

2.0 GPS STATUS

Currently, there are seven research and development Block I (engineering development) satellites in the GPS constellation operating on stable atomic frequency standards and providing reliable ephemeris and time

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information. These satellites are orbiting in two planes separated in longitude by 120 degrees with inclinations of 63 degrees. The operational Block II constellation of 18 satellites will be uniformly spaced in six orbital planes inclined at 55 degrees. Three on-orbit active spares will complement the system. All satellites will be routinely tracked by five Air Force monitor stations whose observations are processed at the GPS Master Control Station in Colorado. Additional tracking at five Defense Mapping Agency (DMA) sites will supplement Air Force collected data for precision orbit determination by DMA for geodetic survey applications. The evolving constellation will support worldwide two-dimensional navigation in 1989 and provide a full three-dimensional navigational capability in 1991.

### **3.0 HYDROGRAPHIC APPLICATIONS**

#### **3.1 GPS Navigation Services**

The operational GPS will provide two distinct navigation services, the Precise Positioning Service (PPS) and the Standard Positioning Service (SPS). The PPS user will have access to both the clear (C/A) code on the  $L_1$  frequency of 1575.4 MHz and to the protected (P) Code on the  $L_2$  frequency of 1227.6 MHz. The SPS user will be limited to the C/A code on  $L_1$ . According to Stein (1986), navigational accuracies from these positioning services are 16.0 and 76.3 meters respectively, spherical error probable. According to Baker (1986), the SPS was designed for civil navigation. If possible, limited civil use of the PPS may be provided. A proposed approach toward making PPS available for civil applications has been formulated and will be coordinated with the civil sector prior to any implementation decision.

In terms of hydrographic applications, these services will provide a positional fix at sea and will provide time relative to the GPS scale. Time transfer using GPS through navigation may be achieved to within 100 nanoseconds using PPS, and 215 nanoseconds using SPS. The navigator will electronically acquire a subset of four satellites from those available to determine three-dimensional position and time by solving directly four equations in as many unknowns. The selection of satellites may be optimized according to predetermined criteria, such as minimizing the sum of the variances of the determined unknowns. Prior knowledge of selected unknowns will either reduce the number of satellite observations required for a position fix or strengthen the solution for the unconstrained parameters. Examples of prior information may include knowledge of the hydrographic platform's mean sea level height or time. Unconstrained, a hydrographic platform's position may be independently determined to the accuracies stated above within a six-second period.

Platform positions may be updated in a continuous fashion to provide subsequent monitoring of the platform's path or updated less frequently with an inertial navigation system extrapolating position and velocity between GPS epochs. The latter approach is accomplished computationally using a sequential algorithm in an aided inertial navigation implementation. This aided approach provides a smoother result than a continuous sequence of independent GPS determinations. Either approach may be appropriate for a surface or airborne survey platform performing hydrographic operations; although due to aircraft velocity, an aided inertial approach may be more critical in aircraft applications.

### 3.2 Dynamic Relative Positioning

Kinematic positioning support of hydrographic applications may be accomplished using GPS to varying accuracy. The nature of the survey will naturally define the positional requirements for such applications. Low accuracy applications typically require 20 to 30 meters and can be achieved using direct positioning with P-code ranging. Medium accuracy, supporting hydrographic or airborne bathymetric survey, may require 5 to 10 meters accuracy which is achievable using dynamic relative positioning with P-code pseudorange. To achieve accuracies on the order of 0.5 to 2 meters or better, it will be necessary to process dual-frequency range and phase or phase alone. The particular application will also differentiate between the need to recover the platform's trajectory and the need to recover intermittent (static) positions along a survey track. As pointed out by Remondi (1986), the consequence may be the requirement (or lack of a requirement) to model receiver processes while traveling between points of interest. Also, depending on the dynamic range of platform motion, receiver loss of lock may be a serious problem to accurately reconstructing the track. Finally, for dynamic relative positioning, the accuracy to which the initial position vector of the platform is known may be a limiting factor in recovering the subsequent platform trajectory. Thus in general, the particular purpose for the survey will be the basis for data acquisition, modeling, and reduction requirements.

The dynamic relative positioning approach for a moving platform usually consists of tracking multiple GPS satellites at one or more fixed sites whose locations are known in a consistent reference frame. By collecting range or phase observations simultaneously with the dynamic platform, ties to the reference frame can be accomplished. The accuracy of such determinations depends on several error sources (Fell, 1980) which will vary to some degree on the geographic separation between fixed and dynamic sites. Estimation equations may be formed in terms of the coordinates of the participating stations. Coordinate differences between the platform and fixed sites and their uncertainties may be obtained by appropriate transformations of the estimation equations.

During the period 1984-1985 several experiments were performed to dynamically position a moving platform. Although several of these experiments were performed with land vehicles, results from these tests are included to provide additional insight into achievable accuracies for ocean platforms. These experiments were conducted under a range of dynamic conditions. Table 1 provides a summary of six of those tests. All experiments used the Texas Instruments TI-4100 GPS receiver. In each test, statically located TI-4100 receivers simultaneously tracked in a common four-satellite mode. The maximum distance of the platform from a static receiver and the dynamic range in platform velocity are indicated in the table. Maximum platform accelerations, exceeding all levels expected in survey applications, may be found for some tests in the references. As expected the observables and rates at which they were acquired, modeling of the data, and the method used to process the observations varied significantly, as did the external standards of comparison used to evaluate the accuracy of the results.

TABLE 1

## GPS DYNAMIC RELATIVE POSITIONING

Author*	Kinematic Test	Dynamic Range		Receiver System	Observable (rate)	Processing Mode	Accuracy Estimates horizontal/vertical	Comparison Standard (Accuracy)
		Max. Distance	Max. Velocity					
Remond	Land August 1985	1 km	25 km/hr	TI-4100	Phase (5 sec)	Triple Differences	1/2.5 cm	Survey Control (several millimeters)
Cannon	Land June 1985	50 km	50 km/hr 135 km/hr	TI-4100	Range Range & Phase (1.2 - 3 sec)	Single Differences	6/7 m 2/2 m	Ferranti Inertial Surveyor (0.3 - 0.8 m)
Seeber	Sea July 1985	1 km	15 km/hr	TI-4100	Phase	Range Change	2/1 m	POLARFIX (.1 m + 20 ppm)
Kleusberg	Land Spring 1985	100 km	50 km/hr	TI-4100	Range & Phase		1/- m	Horizontal Survey Control
Maier	Aircraft July 1985	15 km 150 m vertical	400 km/hr	TI-4100	Phase (3 sec)	Double Differences	-/15 cm	Laser Altimeter
Evans	Vertical Motion November 1984	24 m 3 m vertical	.02 km/hr	TI-4100	Range & Phase (6 sec)	Double Differences	6/6 cm	Survey Control Vertical Motion Calibration

\* See proceedings of the Fourth International Geodetic Symposium on Satellite Positioning for additional details.

At sea in July 1985, a controlled positioning experiment was performed off northern Germany as reported by Seeber (1986). During a three-day period a small vessel equipped with a TI 4100 receiver was tracked with a POLARFIX tachymeter system from a known location. A second GPS receiver simultaneously tracked from a known land site. Dual-frequency GPS phase measurements processed as a range change over time were used in a Kalman filter estimator incorporating no knowledge of platform dynamics. The positions derived from POLARFIX range and azimuth agreed with the GPS positions to better than 2 meters.

In the paper by Mader (1986) a P-3 aircraft equipped with a TI 4100 receiver was flown at an altitude of 150 meters above sea level. Phase data from four satellites were processed by a double difference method with simultaneous data from a second TI-4100 reference site. Observations were acquired at a 3-second rate. GPS range observations were acquired for the purpose of positioning the reference station. The aircraft's distance from the reference site ranged to 15 km. Differences between GPS-derived heights and those obtained from aircraft laser altimetry showed agreement to 15 cm RMS for the best case.

In the experiment described by Cannon (1986), a land vehicle was operated at speeds of 45-50 km/hr and speeds up to 135 km/hr. Range and phase observations were acquired at rates of 1.2 or 3 seconds depending on vehicle dynamics. Pseudorange observations from a common satellite were processed as difference in range between static and platform (moving) receivers; common phase observations were differenced between receivers and differenced again over time forming a change in single differenced phase. Interpolated GPS-derived coordinates over the platform path were compared with positions produced from a Ferranti Inertial Surveyor whose accuracy is 0.3 to 0.8 meters. Range only solutions produced RMS agreement with inertially derived horizontal and vertical control to 6 and 7 meters, respectively. When phase observables were included, results compared at the 2-meter level. Considering interpolation errors (time synchronization between GPS and the inertial surveyor) and the accuracy of the check points, Cannon concluded that the GPS survey may approach an accuracy of 0.5 meters for this application.

Remondi (1986) provided an indication of the accuracy ultimately achievable in (low) dynamic positioning with GPS. The problem of rapidly establishing an extremely accurate initial survey position vector and the determination of subsequent positions was addressed. Using an antenna interchange procedure Remondi demonstrated that an initial survey location, relative to known control, can be rapidly established to less than a centimeter (1-2 mm). Using subsequent phase observations, points along the platform's path were established to an accuracy of 1 centimeter horizontal and 2.5 centimeters vertically. This level of accuracy can be achieved in rapid fashion, since only a few seconds at each point are required to fix the position.

In conclusion, the capability to establish accurate relative positions for a moving survey platform has been demonstrated under quite varying conditions. The accuracy achievable will depend on the observables acquired, the dynamic range of the platform, the corresponding receiver performance, and the data modeling and processing procedures. The accuracy expected will vary from several centimeters to that provided by the PPS or SPS navigation services.



### 3.3 Platform Attitude Determination

Prior to the development of GPS, only inertial measurement systems had the potential to provide both position and platform orientation. A number of proposals have been made to determine platform orientation using phase measurements from multiple GPS satellite tracking receivers (Johnson, et al., 1981; Ellis and Gresell, 1979; and Griffin and Coulbourn 1982). These proposals adopt interferometric methods using the phase of the satellite-transmitted carrier signals measured at the same instant at two or more antennas.

#### 3.3.1 Fixed Antennas

Three points, not in a straight line, define the orientation of a plane with respect to a given coordinate frame. If a vehicle is attached to this plane, then the vehicle orientation is also determined. GPS signals define a coordinate frame which can be related to the fixed Earth. The GPS satellites also provide coded signals which can be received, decoded, and processed with a suitable algorithm to establish the location of the receiver antenna with respect to this coordinate system at a specific time. Repeated processing of the received GPS signals will produce a three-dimensional track of the vehicle's position with respect to time. In a similar fashion, the three-axis orientation of a vehicle can be computed if signals are available simultaneously from three or more antennas.

In order to do three-axis orientation, the three antenna positions must be known relative to each other in a vehicle reference frame. Then, comparison of the phase of the GPS signals received at the several antennas allows one to orient the plane containing the antennas with respect to the GPS coordinate system. This in turn orients the vehicle in the same system.

Simultaneous three-dimensional navigation and three-axis orientation are possible if a suitable receiver and reduction algorithm are available. A time multiplexed receiver may be adapted for tracking four satellites from three antennas simultaneously to give instantaneous navigation and orientation. The system would use software to multiplex the received signals among several software tracking loops. These loops would operate independently on an assigned satellite signal and frequency (L1 or L2).

With a receiver such as the TI 4100 the fundamental clocking interval (T) is 20ms. All receiver operations are some integer fraction or multiple of T. Typically, the receiver dwells for T/2 on each satellite and T/4 on each frequency of a particular satellite. Thus, it completes an observation cycle appropriate for the navigation function using a single antenna (two frequencies and four satellites) after 2T. Collecting data to solve the orientation problem would require an RF switch be inserted between the antennas and the receiver. This switch would be activated in synchronization with the receiver clocking interval. Then, when the switch is operated, the next antenna would be selected to provide signals to its dedicated software tracking loops. In the time between updates of a particular tracking loop, it would extrapolate using the most recent data. Thus, it might be possible to keep several auxiliary sets of tracking loops

(one set per antenna) running in the navigation processor, each set being updated by the receiver processor software. Update intervals of these auxiliary trackers would be at intervals of  $2NT$ , where  $N$  is the number of antennas being used. The receiver would then provide data from all of its tracking loops to an external computer. This computer would contain the navigation-orientation algorithm and display the continuously updated solution.

Orientation accuracies are proportional to the accuracy of the phase difference measurement between a pair of antennas, and inversely proportional to the distance between antennas multiplied by the sine of the angle between the line connecting the antennas and the satellite slant-range vector. Receiver phase measurement accuracies are about 0.005 meter. If an optimal four satellites are always contributing data, then the resulting angular precision should be adequate for many applications. Simulations by Hermann (1984) have shown the accuracies with which GPS can estimate orientation as a function of phase measurement error and baseline length. For example, the standard deviation of the angular estimate, given a 2-meter baseline and a measurement error of 0.005 meters, can approach 3 milliradians.

### 3.3.2 Rotating Antenna

Rather than phase measurements, an alternative procedure uses change-in-phase. Also, instead of using three fixed antennas on a platform, the procedure uses one antenna rotated in the plane of the platform. Therefore, no additional signal channels are required of the receiver in order to determine both real-time position and orientation for low dynamic vehicles.

This platform orientation procedure takes advantage of two physical characteristics. First, the GPS receiver is designed to track four satellites even when the antenna is attached to a high dynamic vehicle. Secondly, movement of the antenna away from, then back to its original location will not change the phase measurements which would have been taken if the antenna had not moved between measurement times (however, compensation for antenna spin must be considered).

The proposed procedure is to periodically change the position of the electrical center of the antenna. The position change is done slowly enough not to lose track, but fast enough with respect to the dynamics of the vehicle. The periodic changes in antenna position imply periodic changes to known positions on the vehicle, which are synchronized in time with the receiver measurements. The procedure is not restricted to a specific type of periodic motion. One of the simplest applications would be periodic circular motion in the plane of the platform. This would be accomplished by placing an antenna at the end of a rotating arm or within a rotating disk.

The accuracy of such a device would depend on a number of factors. Most important are the radius of the circular motion, the change-in-phase measurement accuracy, the vehicle dynamics, the rotational rate, rotational positioning accuracy, and the clock accuracy. Many other types of

configurations are possible and the change in position of the antenna's electrical center could also be accomplished electronically rather than mechanically.

A static demonstration of GPS attitude determination was reported by Evans, et al. (1981) using a Stanford Telecommunications, Inc. (STI) geodetic GPS receiver. The antenna was periodically moved to three locations on a platform. The position changes were made every 15 minutes and done within a 60-second change-in-phase measurement interval. Since this receiver tracks only one satellite at a time, data from repeated position changes were used to emulate tracking multiple satellites during the tracking interval. The root-mean-square error of the demonstrated angular estimates was less than half a degree for the 2-meter baselines. The accuracy of the ionospheric-corrected, phase-differenced measurements was about 2 centimeters for the receiver used in the test. The addition of a similar value for the clock error over the 60-second measurement interval increased the range difference measurements to about 3 centimeters. For a 2-meter baseline, this theoretically translated to a single direction accuracy of about 14 milliradians, or 0.8 degree. This expected accuracy was in agreement with the results of the test case.

The test case demonstrates that in addition to position determination, GPS can be used for orientation. Analysis indicates that GPS orientation determination can be utilized in a wide range of applications.

### 3.4 Marine Geodetic Control

One of the most fundamental challenges presented by an ocean environment is the establishment of geodetic control systems similar to geodetic networks on land. Therefore, methods to obtain accurate marine control which meet the requirements for solving various interdisciplinary problems will require innovative approaches. The applications of such ocean-bottom networks are numerous and well identified within the marine community by Saxena (1980).

In this direction, GPS provides such a capability. The immediate visibility of four to seven satellites anywhere on the earth's surface will make possible instantaneous positioning of a marine platform geometrically. Knowledge of such real time positions will eliminate complex mathematical modeling of platform motion on the ocean surface required of alternative approaches to the solution of the marine control problem.

At any instant, when the platform position is being obtained from GPS, instrumentation aboard the platform could simultaneously be triggered to measure acoustic ranges to a network of ocean bottom transponders. The concept takes advantage of a double pyramid which is formed between GPS satellites and the transponders, linked via the marine platform. The use of remotely operated platforms may be extremely advantageous, providing flexibility and eliminating expensive budgets associated with conventional ship survey.

The measured ranges for any instantaneous double pyramid will constitute a geodetic "event" and these events are solved using the geometric positioning approach described by Mueller et al. (1973) and Kumar (1976), providing a geodetic control network in the marine environment.

In studies performed by Kumar et al (1984) a rectangular network of 25 transponder stations with a grid spacing of 3 minutes of arc was considered. Simultaneous observations to a traversing marine platform were made for two cases, where either five transponder stations participated in an event or where the number varied as a function of the maximum effective acoustical range. This scenario was extended to include three additional stations outside the basic network. These three stations were added to improve the geometry of the system and to eliminate the effect of critical configuration to which networks of limited extent are subject. Transponders were located at an average depth of 2.5 kilometers with total variations in depth of 1 km.

In a least squares adjustment, scale definition is provided implicitly by the observed ranges, while definitions for origin and orientation are required. That information is provided in the form of constraint conditions imposed on the estimation problem. One choice for these external conditions is the "inner" constraints or free adjustment of Blaha (1971), which produces a solution wherein the covariance matrix for adjusted parameters has minimum trace. Geometrically, this implies that the first moments of all transponder station coordinates, as computed using initial coordinate values, will not change after the adjustment and that the sum of rotations of points around all three coordinate axes will be zero. An alternate condition is the imposition of weight constraints on marine platform positions consistent with the PPS navigation accuracy and/or on a selected subset of the transponder network initial coordinates.

An additional consideration is the design of the track patterns to be followed by the marine platform to assure an adequate geometric strength in the recovery of the transponder positions. Track patterns are important to ensure an adequate number of events involving individual transponders and to improve the geometric strength of the pyramid. In an analysis of this concept by Kumar et al (1984), several track patterns were simulated. Although a systematic search for an optimal survey design was not accomplished, track geometries were considered sufficient to reach conclusions on the concept.

The observation frequency for double pyramid events was varied from 150 to 3400 meters of platform travel. The majority of the cases studied were based on 300 meters travel per event. A substantial increase in the frequency of these events will not, in general, benefit the results since the platform-transponder geometry will change insignificantly between observations. Too low a rate will fail to produce a sufficient number of simultaneous events to tie the network together.

In one adjustment, weight constraints were enforced on marine platform positions consistent with the PPS standard deviations on coordinates. Acoustical ranges were not included if the platform-transponder line of sound exceeded eight kilometers. A total of 610 simultaneous events, involving a minimum of five transponders per event, were measured. The results demonstrated that, interior to the network, positional accuracies approach the 10 to 20 centimeter level. As the boundary of the array is

approached, uncertainties increase to 1 to 2 meters with less accuracy in some instances. This is to be expected since the number of simultaneous events involving edge transponders was less than for those more interior to the array. Additional track patterns and types of constraints produced varying results at approximately the same levels.

The results indicate that a remote survey platform as a link between multiple GPS satellites and an acoustic deep ocean transponder network will allow the development of positional accuracies for the transponder array which approach one meter in the GPS coordinate frame. The key to this result is the adoption of platform position constraints consistent with high accuracy GPS navigational capabilities. In addition, the platform track geometry used to survey transponder locations will require optimization in order to exploit this approach to its fullest.

#### 4.0 SUMMARY

Sufficient analysis and preliminary testing of GPS has been performed to provide indications of the success of potential applications of the system on hydrographic survey platforms. These applications include direct navigation, dynamic relative positioning, platform orientation, and the establishment of undersea control networks. Although additional studies are needed to consider the effects of signal multipath, receiver cycle slips, and additional error sources, it is apparent that GPS will be exploited in addition to standard navigation to support precise requirements of hydrographic survey.

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